Transient waveguiding effects during glass processing by bursts of ultrashort laser pulses

K Mishchik, C Javaux Léger, O Dematteo Caulier, Stefan Skupin, B Chimier, G Duchateau, A Bourgeade, R Kling, C Hoenninger, J Lopez

Transient waveguiding effects during glass processing by bursts of ultrashort laser pulses.

K. Mishchik[1], C. Javaux Léger[2], O. Dematteo Caulier[1], S. Skupin[1], B. Chimier[1], G. Duchateau[1], A. Bourgeade[3], R. Kling[2], C. Hönninger[4], J. Lopez[1].

[1] *Université Bordeaux CNRS CEA, CELIA UMR5107, 33405 Talence, France.*
[2] *ALPhANOV, Rue Francois Mitterrand, 33400 Talence, France.*
[3] *CEA/CESTA, 15 Avenue des Sablières, 33114 Le Barp, France.*
[4] *Amplitude Systèmes, France.*

Using femtosecond (fs) laser systems in burst mode is an efficient technique for micromachining of glasses. A burst consists of a group of fs pulses following each other at picosecond (ps) or nanosecond (ns) time scale. While ps-bursts are more effective in glass welding applications [1], ns-bursts are effective for laser drilling of deep holes in glass [2], and they produce lower mechanical strain around laser affected zone (LAZ) [3].

In this article we report on the effect of the ns-bursts on the volume machining of soda lime glass. Laser pulses were provided by an Yb-doped fiber femtosecond laser (Satsuma, Amplitude Systèmes, 5W, 1030nm, 300fs). The By selecting different number of pulses (between 1 and 10 pulses per burst, ppb) from the oscillator working at 40.5 MHz and amplifying them in the Yb-doped fiber (Fig. 1a) bursts with a delay of 25 ns between subsequent pulses were generated. The maximum power after the amplifier working in burst-mode was fixed to 5W. Thus, the energy per burst is constant and shared between the pulses composing each group. Material modifications were obtained by focusing the laser beam with a low numerical aperture objective (NA~0.1) inside the sample (Fig. 1a).

We have investigated the influence of experimental parameters such as numerical aperture, pulse energy, and repetition rate by comparing modifications produced in the LAZ in single pulse or in burst-mode regimes. We demonstrate that in our configuration with fixed energy per burst, the energy deposited in glass decreases while the number pulses in burst increases (see Fig. 1c). This corroborates with the intensity-driven mechanisms of absorption. Nevertheless, burst-mode affects the nonlinear propagation as shown in Fig. 1b. The filamentary-type LAZ is longer and has smaller diameter in ns burst-mode, as a result of a more uniform energy absorption compared with the single pulse machining (see Fig. 1b).

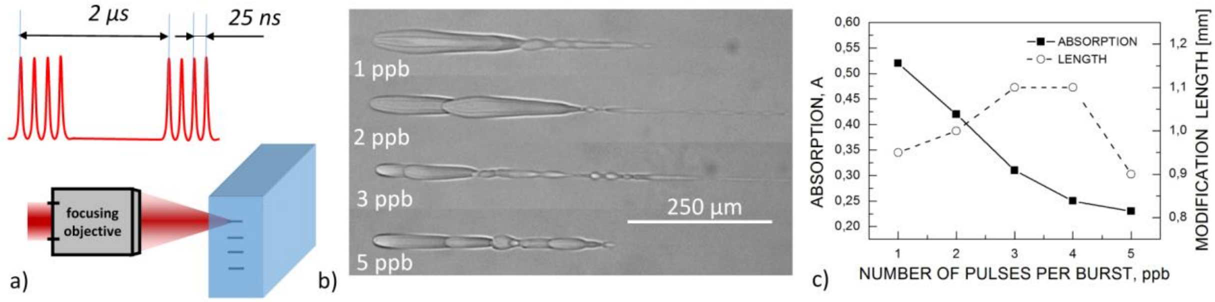

Fig. 1 a) Experimental setup of glass processing in burst operation mode. b) Microscopy image of the LAZ, produced with bursts of 4µJ at 500 kHz repetition rate. c) Deposited energy and the length of LAZ versus number of ppb.

We have analyzed the energy deposition inside the glass by considering thermal effects during laser irradiation. The theoretical numerical model is based on nonlinear light absorption and nonlinear propagation accounting for the generation of the free electrons and the optical Kerr-effect. The model allows us to determine spatial laser energy absorption, which serves as the heat source for the subsequent thermal diffusion and heat accumulation. Simulations show that for a time delay of 25 ns the absorbed energy does not dissipate before the next pulse arrives. Instead, the accumulated heat causes temperature induced band-gap collapse [4] and transient positive refractive index variation at the laser wavelength. On the other hand, temperature-induced volume expansion can lead to a decrease of the refractive index. Such an expansion takes place in a time characterized by the viscoelastic relaxation $\tau_s = \eta/G$, where η is the viscosity and G is the bulk modulus of glass. For the temperatures around the glass transition, which are expected significantly modify material, the previous characteristic time lies in the range of hundreds of ns. We suggest that a competition between these two processes may result in overall positive index changes forming a focusing lens. This lens enables transient waveguiding effect for subsequent pulses arriving at ns time delay which results in the extension of the energy deposition zone.

References

[1] K. Sugioka, S. Wu, K. Midorikawa, "Double-pulsed ultrafast laser welding of glasses toward enhancement of process efficiency", Proceedings of SLPC, 2014.

[2] D. Esser, S. Rezaei, J. Li, P. R. Herman, J. Gottmann, “Time dynamics of burst-train filamentation assisted femtosecond laser machining in glasses”, Optics Express, **19**, 25632, 2011.

[3] F. Zimmermann, S. Richter S. Döring, A. Tünnermann, S. Nolte, "Ultrastable bonding of glass with femtosecond laser bursts", Applied Optics, **52,** 1149, 2013.

[4] K. Saito and A. J. Ikushima, "Absorption edge in silica glass", Physical Review B, **62**, 8584, 2000.